Renewable and Sustainable Energy Reviews 21 (2013) 756–766

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of the islanding detection methods in grid-connected PV inverters

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ARTICLE INFO

Article history:
Received 8 December 2011
Received in revised form
10 January 2013
Accepted 14 January 2013
Available online 28 February 2013

Keywords:
Islanding detection methods
Distributed generation
Non-detection zone
Islanding standards
Inverter

ABSTRACT

Islanding is undesired because it may impair the safety of maintenance service workers and/or damage load equipment through unsynchronized re-closure. In principle, islanding detection is the monitoring of islanding—indicating changes in inverter output parameters or other system parameters. This paper aims to aid design efforts through its comprehensive review of islanding detection methods (comparing their non-detection zones and detection speeds) and anti-islanding standards. As a result, this paper shall provide a handful information and clearer vision for researchers to determine the best method for their product.

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Abbreviations: PV, Photovoltaic; DG, Distributed Generation; NDZ, None detection zone; PCC, Point of common coupling; Q_f, Quality factor; LPS, Load parameter space; PMS, Power mismatch space; $I_{n,a}$, Negative sequence current; OV/UV, Over/under voltage; OF/UF, Over/under frequency; PJD, Phase jump detection; ROCOP, Rate of change of power output; ROCOF, Rate of Change of Frequency; THD, Total Harmonic Distortion; PWM, Pulse Width Modulation; IM, Impedance measurement; PLL, Phase locked loop; SMS, Sliding mode frequency shift; DFT, Digital Fourier transformation; PI, Proportional Integrator; m_f, Modulation frequency; MPPT, Maximum power point tracking; VSC, Voltage source converter; UTSP, Unified three-phase signal processor; ST, S-Transform; WT, Wavelet transform; APS, Active phase shift; SFS, Sandia frequency shift; AFD, Active frequency drift; RPEED, Reactive power export error detection; PLCC, Power line carrier communication; T, Transmitter; R, Receiver; SPD, Signal produced by disconnect; SCADA, Supervisory control and data acquisition; V_{PCC}, Voltage at point of common coupling; V_{load}, Load voltage; Z_{PCC}, Impedance at point of common coupling; Z_{load}, Load Impedance; SNR, Signal-to-Noise Ratio; V_{smin}, Minimum pre-set voltage value; V_{smax}, Maximum pre-set voltage value; RPS, Real power shift; V_{smaxU}, A set point to detect islanding with RPS; VU_{avgt}, Average voltage of 3 phase voltages; THD_{avgt}, Average of total harmonic distortion of phase-A current; V_{avgt}, Average line-to-line voltage; DWT, Discrete wavelet transform; DT, Decision tree; FGNW, Fast Gauss-Newton; FES, Fuzzy expert system

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.01.018

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1. Introduction

Renewable energy has been intensively developed over the past decade. It produces lower pollution than do fossil fuels and nuclear generation systems [1]. The new paradigm of distributed generation (DG) thus increases in technical importance and increases profits globally [2]. In principle, DG is a small-scale generation unit installed to the load and connected to the grid, for selling or buying of energy. Its most important consideration is islanding [1], which, as specified in [3], is the condition when "a portion of utility system that contains both load and distributed resources remains energized while it is isolated from the remainder of the utility system". Such an undesired event could be due to circuit tripping, accidental disconnection of the utility through equipment failure, human error, disconnection for maintenance services, or network reconfiguration (which is uncommon) [1,2]. Integrating DG into utility is a major concern. One problem is that DG may accidentally continue to supply the local load demand when the networks are already isolated from the main system. Successful detection of the islanding is an ongoing challenge to many researchers because existing methods are still not entirely satisfactory [4].

Methods of islanding prevention have been studied. Fig. 1 is a graph of IEEE conferences and journals published on anti-islanding, between 1989 and 2012. From 2002 onwards, it shows that there are an increased of interest on islanding detection.

The 1989–2012 conferences and journals present two types of anti islanding methods: local, or remote. The local methods are either passive or active as shown in Fig. 2.

Passive islanding detection relies on changes to electrical parameters to determine whether islanding had occurred [5]. Its methods were the first to be developed. As technology progressed, more papers discussed active methods, whose development aimed to overcome the limits of passive methods. Remote methods are more reliable but are neither more cost-effective nor simpler to implement than passive or active methods. Section 2 [6] gives examples of passive, active, and remote detection methods. They each have advantages and drawbacks when applied. High demand for the "perfect" method led to much research on wavelet-based islanding detection. Wavelet-based method detects islanding through local measurements of PCC voltage and current signals, just as in passive methods. It is able to evaluate the high-frequency components injected by inverter, just as in active methods [7]. Its main advantage is its sensitivity to signal irregularities such as those in islanding [8].

Two factors aid understanding of islanding: the established standards for grid-connected systems (which address issues of islanding and the procedure for testing and qualifying a DG system) [5], and NDZ (the zone in which an islanding detection method would fail to operate on time, and an evaluating criterium for islanding detection methods).

Section 2 of this paper gives examples of passive, active, and remote methods of islanding detection. The anti-islanding standards are compared in Section 3. Section 4 discusses NDZ in general. Section 5 discusses the primary objective of this paper, presenting past reported principles of detection methods, whose effectiveness are compared before drawing the conclusions.

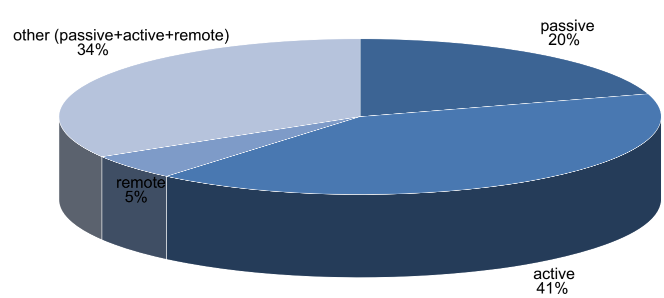

Fig. 2. Types of islanding detection, 1989–2012.

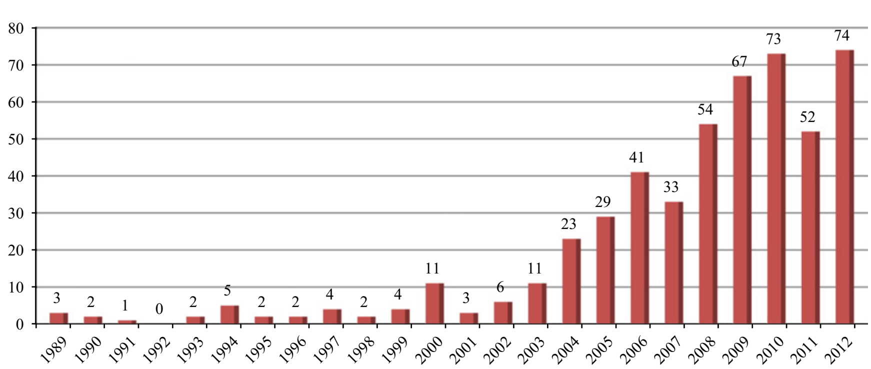

Fig. 1. Papers on anti-islanding, 1989–2012.

2. Islanding detection methods

In grid-connected PV inverters, the methods of islanding detection fall into 3 categories: passive islanding, active islanding, and remote islanding.

2.1. Passive islanding

Passive islanding techniques rely on parameter thresholds. Their advantages are easy implementation (controller not required), no degradation of the PV inverter power quality, and inexpensiveness. Their primary drawbacks are a relatively large NDZ and their ineffectiveness in multi-inverter systems [9,10]. The most commonly used passive islanding detection techniques are over/under voltage and over/under frequency (OV/UV & OF/UF), phase jump detection (PJD), voltage harmonic monitoring, current harmonic monitoring, rate of change of power output (ROCOP), and rate of change of frequency (ROCOF). The following are important requirements and descriptions on how most of them work.

2.1.1. Over/under voltage and over/under frequency (OVP/UVP and OFP/UFP)

This basic method is based on setting a threshold value for voltage and frequency at the point of common coupling (PCC). Basically, there will be disconnection in the circuit if the value of voltage or frequency is not within the standard limits. Most of the standards usually have their own normal voltage/frequency ranges. Note that the protection method is implemented in software, typically, rather than in actual relays. At PCC,

$$\Delta P = P_{Load} - P_{PV} \tag{1}$$

$$\Delta Q = Q_{Load} - P_{PV} \tag{2}$$

The system basically depends on ΔP and ΔQ just before the grid disconnects, to form an island. If $\Delta P \neq 0$, the amplitude at PCC will change, OVP/UVP detects the change, disconnecting the inverter. If $\Delta Q \neq 0$, the load voltage will show a sudden phase shift, leading to a change in the frequency of the inverter output current. OFP/UFP will detect this change and disconnect the inverter. The main advantage of this method to researchers of islanding detection is its low cost [1,11] (Fig. 3).

Table 1
Harmonic limits of the test voltage [16,17].

Harmonics order number	3	5	7	9	11	13
Limit based on percentage of fundamental	4%	2%	1.5%	0.6%	0.1%	0.1%

2.1.2. Phase jump detection

Phase jump detection is a method capable of deactivating the inverter if there is a phase difference detected between the inverter output voltage and the inverter output current, such as during islanding. Its main advantage is its effectiveness, even with multiple inverters. Still, the threshold value must be chosen correctly to provide reliable islanding detection without any frequency nuisance trips. Below is equation for phase-jump algorithm (3) [1,11,12]:

$$\arctan\left(\frac{(\Delta Q/P)}{1+(\Delta P/P)}\right) \leq \vartheta_{threshold} \tag{3}$$

2.1.3. Monitoring of voltage and current harmonics

This method proposes two parameters for islanding detection: THD and the main harmonics (3rd, 5th, and 7th) of the PCC voltage. If these values exceed a specific limit, the inverter shuts down. During normal operation, the PCC voltage equals the grid voltage, hence the distortion is usually negligible (THD $\approx$ 0). During islanding, two mechanisms can cause the harmonics at PCC to increase:

1. Current harmonics produced by the PV inverter are transmitted to the load,
2. Magnetic hysteresis and other non-linearities in the transformer cause high distortion to the voltage response, increasing THD.

The effectiveness of this method does not temper much in multiple inverter configurations, but it still has that problem of not having an ideal tripping threshold for reliable islanding protection. This method may also fail with high value of Q. A typical condition for a grid-connected PV inverter is that its THD must not exceed 5% of its full rated current. Values of the harmonic limits of the test voltage according to AS4777.2-2005 are as listed in Table 1 [1,11,13–15].

2.1.4. Rate of change of frequency (ROCOF)

When the grid supply is lost, the system comprising inverter and load becomes islanded. There is thus a power imbalance, which causes transient in the islanded system, and the frequency slowly changes. This change *(df/dt)* is measured over a few cycles,

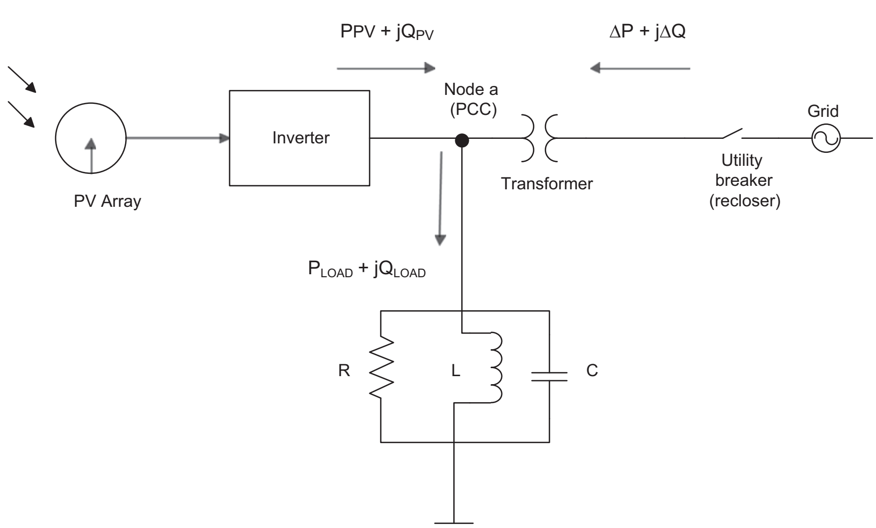

Fig. 3. PV System/Utility Feeder Configuration, with definitions for power flow and terms [11].

usually 2–50 cycles. If the change rate exceeds the pre-set value, the inverter shuts down. A ROCOF relay monitors the voltage waveform and trips up the circuit breaker when frequency change rate exceeds the threshold for longer than the preset time-delay. In small and medium DG units, a trip setting of 0.3 Hz/sec has been found to be the optimum value, with 0.3 s–0.7 s operating time. With extreme frequency changes, the tripping time could be set to less than four or five cycles [18,19].

2.1.5. Rate of change of power output (ROCOP)

As grid loss generally produces load change, monitoring of the changes in the DG power output provides direct detection of islanding. This method monitors all the changes in the power output and integrates those changes over a defined sample period. Tripping occurs when the signal exceeds the trip settings. The method can quickly detect unsynchronized reconnection of the utility supply to a power island containing the DG unit [18].

2.2. Active islanding

Active techniques inject a small disturbance at the PV inverter output for islanding detection. Their main advantage is relatively smaller NDZ than that in passive methods. Their main drawbacks are the possibility of deteriorating output power quality destabilizing the PV inverter, and the need (usually) for additional controllers increasing complexity [9,10]. Existing active techniques are given next.

2.2.1. Impedance measurement (IM)

This method detects islanding through inverter output impedance changes, caused by loss of the main power. It has many weaknesses, especially the reduced effectiveness as the number of inverters connected to the grid increases (unless all the inverters are somehow synchronized). Another is the necessity to set an impedance threshold to signal that the mains is connected (this requires an exact value of the grid impedance, usually very small). [20] showed indirect method used to measure impedance by introducing a small high-frequency (HF) signal as input to a voltage divider and connected to the mains through a coupling capacitor. The voltage divider circuit changes the output voltage, from which islanding can be detected. All the weaknesses of this method have led some to conclude that it is sometimes impractical [20,21].

2.2.2. Sliding mode frequency shift (SMS) or active phase shift (APS)

The slide (or slip) mode frequency shift uses positive feedback to the phase of the voltage at PCC to shift the phase (and hence the short-term frequency). [22] proved the method's robustness through a SPICE-based model simulation. Usually, DG operates at unity power factor, so the phase angle between the PCC voltage and the inverter output current is controlled at zero. In SMS method, the current–voltage phase angle is made to be a function of the frequency of the PCC voltage. Usually this method will be implemented through the use of an input filter to the PLL. The authors of reference [23] proved that in the Q_f versus f_0 space, this method can be designed to ensure islanding detection in an RLC load with a small quality factor, but as the load quality factor increases, the method's effectiveness decreases [22,23].

2.2.3. Sandia frequency shift (SFS) or active frequency drift with positive feedback

This method is the accelerated version of active frequency drift (AFD). It uses positive feedback to prevent islanding. With connection to the grid, it tries to amplify small changes in frequency but the stability of the grid prevents it. When the grid disconnects, changes to the frequency produce a phase error. The process continues until the frequency exceeds the threshold of OF or UF. To implement positive feedback, the "chopping fraction" is defined as:

$$C_f = C_{f_0} + K(f_a - f_{grid}) \tag{4}$$

with C_{f0} the chopping fraction when there is no frequency error, K the accelerating constant that does not change direction, f_a the measured frequency of the voltage at PCC, and f_{grid} the grid frequency. SFS method is known as one of the active methods that have small NDZ. It depends on its parameters C_{f0} and K. [24] shows that the performance of this method depends on the parameter K. Simulation results show that the mathematical formula derived to optimally set this parameter is highly effective and able to eliminate NDZ. In [25], the same author tested this method with multiple DGs and validated it through simulation results [11,24,25].

2.2.4. Reactive power export error detection (RPEED)

An RPEED relay combined with a DG control system generate a level of reactive power flow in the inter-tie between the DG and the grid. Islanding is detected through relay tripping, once the grid connection is lost. The relay tripping is triggered by the error existed between the setting and the actual reactive power being exported for a time period longer than the pre-set value. The operating time for this method is typically 2–5 s; it is thus suitable only as backup protection. It nevertheless is considered more effective than passive method, especially for small-load changes or no-load changes during off-grid [2,21].

2.3. Remote techniques

Remote islanding detection techniques are based on the communication between the utility and the PV inverter unit [10]. This technique does not have NDZ and does not degrade the PV inverter power quality. In multi-inverter systems it is effective but expensive to implement (especially in small systems) and has a complicated communication technique. Next are common communication-based techniques.

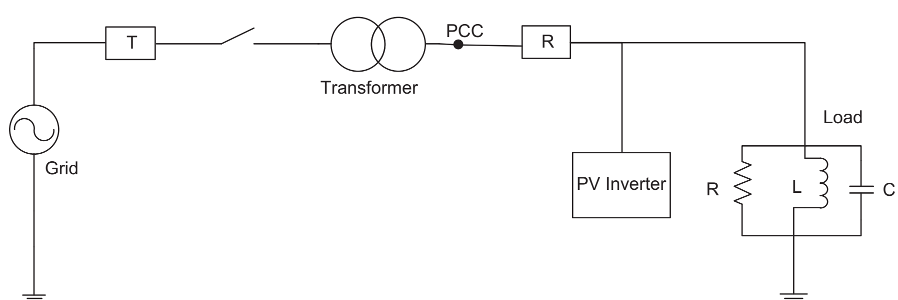

Fig. 4. Anti-islanding method based on PLCC with transmitter (T) and receiver (R) [26].

2.3.1. Power line carrier communication (PLCC)

In principle, this method uses a low-energy communication signal along the power line. A transmitter (T) is placed near the grid protection switch, and a receiver (R) is installed at the PCC as shown in Fig. 4. Without islanding, a low energetic signal is transmitted to the receiver. During islanding, communication stops the data transmission, ordering the inverter to trip. This scheme has been proven to be very effective in multiple-DG configurations. Several properties must be complied with by the transmitter signal to ensure smooth islanding detection. Firstly, the signal must be sent continuously, then the signal frequency must be low because of transformer inductance (which acts as a low-pass filter), and lastly the signal must able to travel from the grid to the load [6,12,26].

2.3.2. Signal produced by disconnect (SPD)

This method is similar to PLCC. The only difference is the type of transmission used (microwave link, telephone link, or others). Its switch state is directly communicated to the DG. Its strengths are additional supervision and full control of both the grid and the DG. Its drawbacks, however, include relative expensiveness, also possible/significant licensing and design complications [1].

2.3.3. Supervisory control and data acquisition (SCADA)

A supervisory control and data acquisition (SCADA) system monitors the auxiliary contacts on all utility circuit breakers that are liable to check the conditions of islanded operation. Upon islanding, a series of alarm is activated and the corresponding circuit breaker is tripped. This method is highly effective in detecting islanding, but it is too expensive and requires many sensors. Its drawback is that it is rather slow, especially when the system is busy (with disturbances). A small inverter configuration is not recommended, due to the utility's huge involvement in inverter installation, and to the permitting process [27,28].

3. Anti-islanding standards

Among the popular reference standards for islanding include IEEE 929-2000, IEC 62116, IEE 1547, VDE 0126-1-1, and AS 4777.3-2005. These standards have been fully utilized to help the researchers in designing their product.

Table 2 shows all the standards as having their own Q value, islanding disconnection time, frequency and voltage operation range [1]. According to IEEE929-2000 standard, Q is:

$$Q = \tan(\text{arccosine}[\text{pf}]) \qquad (5)$$

The selected Q of 2.5 equals to 0.37 power factor. As power factor increases, Q decreases. The test requirement that Q=2.5 is equal to lines with uncorrected power factors from 0.37 to unity; this seems to reasonably cover all distribution line configurations [3]. Japan standard proposes that Q equals 0 and that rotating machinery is added during islanding test [1]. Besides Q, islanding disconnection time is also crucial. The German VDE0126-1-1 has the strictest disconnection time limit: below 0.2 s. Normal frequency and voltage range also are important to islanding detection. Australian standard AS4777.3-2005 requires that nominal frequency and voltage range be set by manufacturer. Steps to obtaining trip values are: (1) determination of under/over voltage and under/over frequency values through gradual increase or decrease of voltage and frequency until the device tested (the inverter) disconnects from the variable ac supply, and (2) reading of the over/under voltage or over/under frequency values at which disconnection occurred. A criteria of acceptance for over/under voltage is that the value at step (2) should equal an under-voltage set point of ± 5 V; for frequency, the value should equal an under-frequency set point of ± 0.1 Hz [16,17].

Fig. 5 shows a typical anti-islanding test circuit for PV grid-connected inverter as outlined by IEEE 929-2000.

4. NDZ

NDZ enables determination of the best method, which is the one with the smallest NDZ area [29]. [9] proved that passive islanding has larger NDZ than does active islanding. NDZ can be detected/analyzed 2 ways, either by load parameter space (LPS) or by power mismatch space (PMS) [1].

- LPS is suitable for islanding detection that is based on frequency drifting [30]. LPS or RLC load space, predicts NDZ through zero phase error (called phase criteria) between the PV output current and the terminal voltage. Through the phase criteria, NDZ can be mapped out to normalized C_{norm} against load inductance (L). This method can predict the NDZ location for each method but not the method's disconnection time. Ropp et al. proved that the worst case of islanding detection involves loads that have high Q factor [29] (Table 3).
- PMS exploits the power mismatch in R, L, and C. The power mismatch is controlled by the grid, but when the grid is

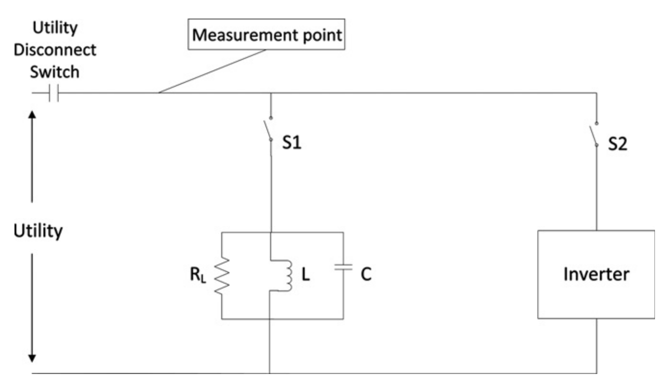

Fig. 5. Anti-islanding test circuit [3].

Table 2
Reference standards for anti-islanding [1].

	Quality factor, Q_f	Required islanding detection time, t	Normal frequency range, f (*nominal frequency* f_0)	Normal voltage range, V (*% of nominal voltage* V_0)
IEC 62116	1	$t < 2$s	$(f_0 – 1.5\text{ Hz}) \le f$ and $f \le (f_0 + 1.5\text{ Hz})$	$85\% \le V \le 115\%$
IEEE 1547	1	$t < 2$s	$59.3\text{ Hz} \le f \le 60.5\text{ Hz}$	$88\% \le V \le 110\%$
IEEE 929-2000	2.5	$t < 2$s	$59.3\text{ Hz} \le f \le 60.5\text{ Hz}$	$88\% \le V \le 110\%$
Japanese standard	0(+rotating machinery)	Passive:$t < 0.5$s Active:$0.5s < t < 1s$	Setting value	Setting value
Korean standard	1	$t < 0.5$s	$59.3\text{ Hz} \le f \le 60.5\text{ Hz}$	$88\% \le V \le 110\%$
VDE 0126-1-1	2	$t < 0.2$s	$47.5\text{ Hz} \le f \le 50.2\text{ Hz}$	$80\% \le V \le 115\%$
AS4777.3-2005	1	$t < 2$s	Setting value	Setting value

Table 3
Phase criteria for several islanding prevention methods [29].

Islanding prevention scheme	Phase criterion	How to use phase criterion (PC)
OFR/UFR	$\tan^{-1}\left[R\left(\omega C-\frac{1}{\omega L}\right)\right]=0$ $\Downarrow$ $\omega C-\frac{1}{\omega L}=0$	If ω at which the P.C is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ
PJD	$\tan^{-1}\left[\left(R\left(\omega_0 C-\frac{1}{\omega_0 L}\right)\right]\le\phi_{th}$	If the P.C. is satisfied at ω_0 (line frequency), the RLC load is inside the NDZ
SMS	$\tan^{-1}\left[R\left(\omega C-\frac{1}{\omega L}\right)\right]=-\arg((G(j\omega))$	If ω at which the PC is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ
AFD	$\tan^{-1}\left[R\left(\omega C-\frac{1}{\omega L}\right)\right]=-\frac{\pi cf}{2}$	If ω at which the PC is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ
SFS	$\tan^{-1}\left[R\left(\omega C-\frac{1}{\omega L}\right)\right]=-\frac{\pi(cf_{k-1}+K\Delta\omega)}{2}$	If ω at which the PC is satisfied lies within OFR/UFR trip limits, the RLC load is inside the NDZ

Table 4
Comparison of the principle methods for islanding.

Principle method of detection	Classification	Speed of detection/ run-on time	NDZ
Harmonics/THD	Active method [34] (Goertzel algorithm)	0.4 s	None
	Passive method [35] (Grid voltage sensorless)	45 ms	None
Frequency	Passive method [10] (OF/UF)	Within 2 s	Large
	Active method [37] (a novel AFD)	Within 2 s	Exist but less than conventional AFD method
	Active method [5] (virtual resistor method)	39 ms (with Q=2.5)	None
	Active method [39] (virtual capacitor method)	51ms (with Q=2.5)	None
	Active method [38] (improved AFD)	Within 2 s	Very small
Changes of impedance	Passive method [36] (switching frequency)	20 ms	None
	Active method [40] (PLL)	0.95 s	None
	Active method [41] (PI & predictive controller)	0.77 s	Very small
	Active method [42,43] (high frequency signal injection)	A few milliseconds	None
Power variation	Active method [44] (effective power variation with AFD)	0.3 s (with Q=2.5)	None
	(reactive power variation) [45]	Less than 2 s	None
	Active methods[46,47] (voltage positive feedback)	250 ms	None
Negative sequence voltage at PCC	Active method [33] (injecting a disturbance signal of negative-sequence current)	120 ms	None
	Active method [48] (injecting a disturbance signal of negative-sequence current)	60 ms (3.5cycles)	None
	Active method[49] (reducing the magnitude of the injected current)	400 ms	Very small
	Passive method [50] (Fuzzy & S-Transform)	Less than 20 ms (less than 1 cycle)	Very small
Wavelet	Passive method [51] (wavelet)	50 ms (2.5 cycles)	Almost zero
	Passive method [52] (wavelet coefficients of transient signals)	24 ms	None
	Passive method [53] (discrete wavelet transform)	5.5 ms (for 60 Hz)	None
	Passive method [54] (wavelet packet transform)	Very small	None
	Passive method [55] (discrete wavelet transform)	Less than 20 ms (less than 1 cycle)	None
	Passive method [56] (wavelet transform & S-transform method)	Very small	None
Combination	Active method [58] (combination of voltage amplitude and frequency at the PCC)	33.3 ms	Very small
	Passive method [59] (combination of voltage amplitude and frequency)	150 ms	Very small
	Active & passive method [60] combination of a rate of voltage change (passive) and real power shift (active)	Within 2 s	Small
	Passive method [61] (combination of voltage unbalance and total harmonic distortion of current)	Within 2 s	None
	Passive method [62] (fast Gauss Newton algorithm)	Under 20 ms (under 1 cycle)	Very small

disconnected, the power mismatch increases, putting the voltage and frequency out of its nominal value [31].

$$\left(\frac{V}{V_{\max}}\right)^2-1\le\frac{\Delta P}{P}\le\left(\frac{V}{V_{\min}}\right)^2-1 \tag{6}$$

$$Q_f\left(1-\left(\frac{f}{f_{\min}}\right)^2\right)\le\frac{\Delta Q}{P}\le Q_f\left(1-\left(\frac{f}{f_{\max}}\right)^2\right) \tag{7}$$

As outlined by IEEE 929-2000, where $V_{\max}$=110%, $V_{\min}$=88%, $f_{\max}$=60.5 Hz, $f_{\min}$=59.3 Hz, and Q_f=2.5. The equation can be

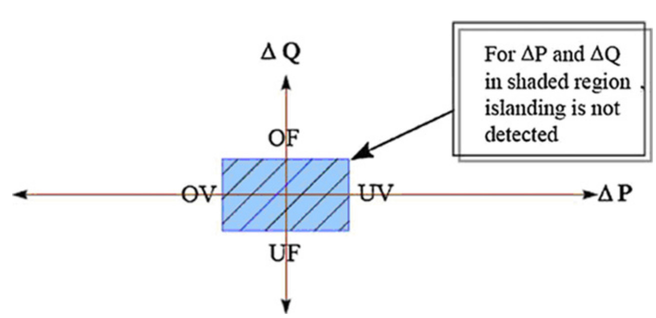

Fig. 6. NDZ mapping in ΔP versus ΔQ space for OUV and OUF [11,29,32].

derived as:

$$-17.36\% \leq \frac{\Delta P}{P} \leq 29.13\%$$

$$-5.94\% \leq \frac{\Delta Q}{P} \leq 4.11\%$$

From (6) and (7), Zhihong Ye et al. proved that if the active power and reactive power mismatches are within the specified range, the operating frequency and voltage will remain inside the nominal range, making islanding detection impossible. From both the equations, NDZ area can be mapped as in Fig. 6. This paper also highlights that each Q will have its own NDZ, and the smaller the Q_f, the smaller the NDZ [31].

Many papers have published ways to eliminate or reduce NDZ. Behrooz Bahrani et al. [33] validated their NDZ-eliminating approach in an active islanding method. They analytically analyzed and proved that the method has an NDZ in LPS owing to the effect of unbalanced three-phase RLC load. Basically, active islanding method injects a negative sequence current as a disturbance signal to a DG system. Islanding is detected through the corresponding negative sequence voltage at PCC.

NDZ is eliminated by a slight modification to the control algorithm; the phase angle of the injected negative-sequence current $I_{n,a}$ is technically changed periodically between zero and π. The modification uses a periodic pulse as the reference signal of the negative-sequence current controller. Note that the paper also tested and evaluated the islanding method on various types of two-DG configurations.

Zeineldin et al. [9] proposed a simple passive islanding technique with negligible NDZ. They proposed a simple OV/UV method that detects voltage deviation upon islanding. They also verified and concluded that different values of reference power expressed as a function of voltage will reduce or increase NDZ. The PSCAD/EMTDC simulation result of [9] proved that the use of power voltage expression with positive slope reduces NDZ. They also verified that setting the slope of the power voltage expression tangential to the active power output results in negligible NDZ. The mathematical operation developed can be simply implemented in the control algorithm. Future work may include experiment result supporting the existing simulation result.

5. Research review: principle of detection method

A good islanding detection method ensures reliable detection. This section elaborates on the principle of the islanding detection methods commonly used now: detection of THD or harmonics, frequency of PCC voltage, changes to the grid impedance, power variation, voltage at PCC, wavelet detection, even combinations of several detection methods into one. The followings are the summary of the works done based on the above mentioned ways of islanding detection:

5.1. Detection of THD or harmonics

[34] proposed a system that injects the output current with a ninth harmonic component that is less than the pre-defined standard into the grid, and through Goertzel algorithm detects the ninth harmonic component of the V_{pcc}. The Goertzel algorithm is a kind of discrete Fourier transformation that extracts from the input signal, the phase and magnitude of the desired frequency. When islanding occurs, V_{PCC} and V_{load} become equal, and hence, so do Z_{pcc} and Z_{load}. The proposed method detects the magnitude of the ninth harmonic and stops the system within two periods due to the appearance of the injected ninth harmonic current in the V_{PCC}. The advantage of this technique is that any order of the harmonic (third, fifth, and seventh), or two or more harmonics side by side, can be chosen.

The authors from the reference [35] have validated the islanding detection capability of their proposed method (which modifies a three-phase system through use of resonant controllers to make it suitable for single-phase systems, and uses a grid voltage sensorless algorithm). In principle, grid voltage sensorless method compares the predicted voltage with the real ones. The voltage is predicted by assuming that the grid is present, and that when the grid is missing, the algorithm will suffer a transient that is stronger (case of DG system power equaling load power) than that of a system adopting grid voltage measurement. The authors developed the Kalman filter (KF) algorithm to detect this transient. The system detects islanding by comparing the estimated grid voltage with the measured grid voltage through the energy associated with each of the harmonic error. The method was successfully tested with real grid conditions and nonlinear load.

5.2. Detection of frequency

Two examples from passive islanding detection based on frequency detection are basic OF/UF and ROCOF. Frequency change rate is one of the common methods used in the United Kingdom and Europe [36]. [10] proposed basic passive islanding detection through TMS320F2812 DSP, for OF/UF; the frequency is calculated from the instantaneous voltage value from the first zero crossing until the third. DSP increases the counter value while reading the voltage value for N sampling time. The frequency data are then stored in the memory register and compared with the pre-set threshold value in the islanding detection algorithms. If the memory's data exceed the pre-set threshold value, the DSP sends a signal to turn off the relay that disconnects the system.

An active islanding method that also uses frequency to detect islanding is AFD. It varies the output current frequency through positive feedback. It injects a current with slightly distorted frequency into the PCC. Upon grid disconnection, the phase error between the PCC voltage and the inverter current is detected by the inverter, which then tries to compensate by increasing the

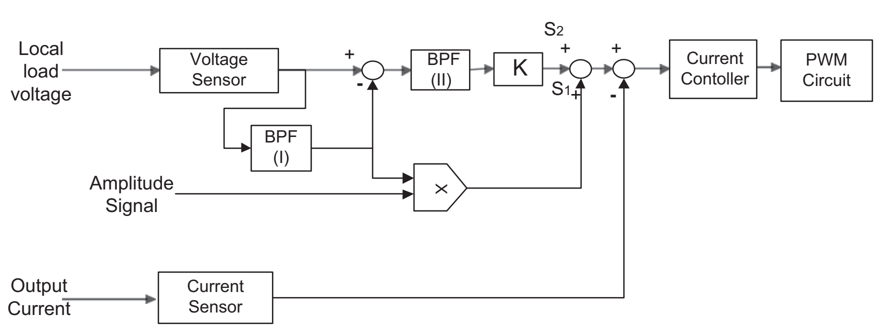

Fig. 7. Control of the grid-connected inverter as virtual resistor or virtual capacitor [5,39].

frequency of the injected current until it exceeds the OF/FU limits. Its performance is poor, however, and a suitable chopping fraction (*cf*) value to meet the harmonic limits is hard to choose. Hence, a novel AFD method [37] with a periodic chopping fraction that deviates from the frequency instantly from nominal is proposed. Another problem in conventional AFD method is the amount of THD injected into the grid. THD usually defines the NDZ of a method. Ahmad Yafaoui et al. [38] proposed an improved AFD method that can detect islanding with less THD compare to the conventional AFD. Simulation and experiment results show the proposed method to produce 30% less THD in the current waveform. The proposed method is based on a different current distortion injection waveform. The RMS value and the Fourier series coefficient of the proposed current waveform are obtained and used to derive analytically some of the operational characteristic of the method.

Wen-Jung et al. [5,39] proposed an active islanding method incorporated into the control of a grid-connected inverter that acts as a virtual resistor [5] or virtual capacitor [39]. For virtual-resistor operation, the frequency is slightly higher (80 Hz) or lower (50 Hz) than the grid voltage frequency (60 Hz). For virtual-capacitor operation, the frequency is slightly lower than the grid voltage frequency. Neither the virtual resistor function nor the virtual capacitor function is activated when the grid is connected. With grid loss, the grid-connected inverter acts as a virtual resistor or a virtual capacitor. Islanding is thus detected from variations in the local load voltage amplitude and frequency. Analysis and experiment results verified that the proposed method can effectively detect islanding with various load types and quality factors. Fig. 7 is a diagram of the control used in [5,39]. The grid-connected inverter is controlled by the current-mode controller. The controller output is sent to a PWM circuit to generate the proposed PWM signals.

5.3. Detection of impedance

Because of the small NDZ, impedance monitoring became one of the most popular methods researched for active islanding detection. There is an initiative by researchers in developing an active method that introduces fewer disturbances to the DG system. An example is the method developed by M. Cionbotaru et al. [40] which is based on phased-locked loop (PLL) controller and grid impedance changes. [41] also proposed an active method; it combines PI and predictive controllers to generate the reference current and the inter-harmonic current for injection into the DG system. The authors adopted DFT algorithm to finally estimate the grid impedance for islanding detection.

Soo-Hyong Lee et al. [36] reported the development of a passive method to determine islanding through impedance detection that uses the switching frequency of a PWM inverter. The authors proved that impedance during islanding is much larger than that in pre-islanding. The proposed modulation frequency (*mf)* is 21–330, with the usual switching frequency being 1260 Hz–20 kHz. The idea is that islanding can be detected through variation in impedance with respect to inverter switching modulation. [36] concluded that this method:

(a) has zero NDZ;
(b) does not cause any intended changes in reactive power or harmonics variation to the DG system as do other active methods;
(c) is successful in detecting islanding in single and multiple grid-connected DG systems as proven by PSCAD/EMTDC simulation in [36] (within 20 ms).

David Diaz Reigosa et al. [42,43] proposed a new active method that measures the high-frequency impedance of the grid. This method injects a high-frequency signal for islanding detection of microgrids. It relies on variations in the high-frequency impedance measured, obtained from the output current estimated and the output voltage measured, of the LCL filter, through complex-vector filters. This method detects islanding in the range of a few milliseconds.

5.4. Detection of power variation

Many anti-islanding detection methods degrade power quality. One literature suggests that high power quality can be had with high islanding-detection capability [44]. The technique uses effective power variation, a periodic increase or decrease of the inverter output current magnitude. Such variation keeps the total average real power from the PV to be constant without affecting the maximum power point tracking (MPPT) function of the PV inverter. Results of the proposed method show the reference current varying proportionally with deviations in the inverter output voltage after islanding. If the inverter output voltage varies largely, AFD method will be activated for a limited period to detect islanding. Positive and negative chopping fractions were used here to improve transient response.

Jun Zhang et al. [45] proposed an improved islanding method that is based on intermittent bilateral (IB) reactive power variation (RPV). The variation scheme proposed for this method is the setting of the reactive power reference. The proposed method monitors system frequency and determines islanding once the frequency runs out of the normal range. It detects and controls the inverter output reactive power to the required variation. This technique has been validated by a three-phase grid-connected inverter with 6 kW active power. The experiment results show the intermittent bilateral reactive power variation (IBRPV) method capable of eliminating NDZ in less than 2 s.

In [46], an active islanding detection algorithm proposed by the same author in [47] was validated for multi-inverter system configurations. The proposed algorithm is based on positive voltage feedback. The rms voltage measured at PCC is taken as feedback variable V_{rms}. Variations of V_{rms} are then used to generate a limited active power perturbation (ΔP). Synchronization of DG units is not required because all the units use the same variable (V_{rms}) to generate their local anti-islanding protection. The experiment results verified that islanding could be confirmed within 250 ms on 60 Hz utility voltage.

5.5. Detection of negative sequence voltage at PCC

Behrooz Bahrani et al. [33] proposed an active islanding method in which a negative-sequence current controller injects a disturbance signal of negative-sequence current. With grid connection, the injected negative-sequence current flows to the grid. Without grid, the injected negative-sequence current flows to the load, unbalancing the PCC voltage. The magnitude of the corresponding negative-sequence voltage at PCC is used to detect islanding; if it exceeds the threshold, the system is islanded.

Houshang Karimi et al. [48] also proposed similar active islanding detection, which injects a small negative-sequence current through a 3-phase VSC controller and detecting the corresponding negative-sequence voltage at PCC through a UTSP (which basically is a modified PLL, is more immune to noise, so is reliable for detection of small magnitude negative-sequence voltage). The UTSP introduced also precisely detects negative-sequence voltage even when the signal is polluted with a 30 dB signal-to-noise ratio (SNR) Gaussian white noise. PSCAD/EMTDC simulation shows the proposed islanding detection method able to detect islanding within 60 ms (3.5 cycles) under UL1741 test conditions.

Another active islanding method, developed by Indu Rani et al. [49], monitors PCC voltage. It depends on changes to the magnitude of the injected current. The current is perturbed by reducing the magnitude of the reference current to 80% of I_{ref}, for 2 cycles. As only the current magnitude reduces, the perturbation does not affect power quality as do other active islanding techniques. When the grid disconnects, the PCC voltage change exceeds the allowable range, and islanding is detected. The simulation was on MATLAB/Simulink, and the algorithm was implemented on ALTERA CYCLONE FPGA. The detection time for the worst case in the proposed method was 400 ms.

Dash et al. [50] proposed a new time-frequency approach for power island detection in DG systems. It uses a hybrid of a fast variant of the S-Transform (ST) algorithm and an FES. The negative sequence voltage and current signals from the DG system are obtained through the fast ST. These features are then used as inputs to the FES to detect islanding.

5.6. Wavelet

Many papers have been recently published on wavelet-based islanding detection. This method is basically a passive method; it does not introduce any disturbances to the system. It will eliminate NDZ without any disturbances that can deteriorate output power quality.

DWT is a signal processing tool that can be used when time-varying harmonics must be evaluated, and, as in islanding detection, time localization is required [51]. Use of DWT enables a signal's decomposition into several signals of different frequency bands, called wavelet coefficients.

The wavelet coefficient for voltage or frequency signal is compared with the preset threshold value. If the relevant wavelet coefficient remains above the preset threshold value for a time longer than the pre-set time threshold, islanding will be detected. The pre-set threshold value shall be determined through the simulation and experiment result.

[52] investigated an intelligent method that is based on the wavelet coefficients of transient signals. A trained DT classifier that uses the energy associated with the wavelet coefficients is the islanding detector. The proposed method always responded in less than 24 ms every time islanding occurred.

[53] introduced islanding detection that is based on wavelet packet transform. It uses only the local measurement of voltage and current at PCC. In [54], this method detected islanding only by evaluating the current signal at PCC. Its primary advantages are its suitability for use in multiple-DG configurations and its ability to detect islanding within less than one third of a cycle, i.e., 5.5 ms, for a 60 Hz grid frequency.

The first paper published on wavelet-based islanding detection algorithm was by Alberto Pigazo et al. [7,55], in 2007. They proposed a detection method that takes advantage of the time and frequency localization of the DWT, which is applied to the high-frequency components introduced by the distributed power generation system inverter at the PCC. It is considered a passive method because its ability to detect islanding is based on the voltage and current signals at PCC.

In [56], Ray et al. compared WT with ST through the extracted features for islanding detection in hybrid DGs. The hybrid system consists of DG resources such as PV, fuel cell, and wind energy connected to the grid. The method uses the negative sequence component of the voltage signal in islanding detection. The results showed ST to be more advantageous than WT.

As a conclusion, wavelet-based detection is a passive technique that performs as good as an active technique, and is no doubt the new future technique for anti-islanding [57].

5.7. Combination of detection methods

There has also been much effort into combining the various methods. It considers the advantages of each method and combines them for best results. The following are several combination islanding detection methods.

(a) Combination of voltage amplitude and frequency at the PCC: This method injects a disturbance signal through either the direct axis (d-axis) or the quadrate axis (q-axis) current controllers of the interface VSC. Signal injection through the d-axis controller will modulate the amplitude of the voltage at PCC. Meanwhile, signal injection through the q-axis controller will cause frequency deviation at PCC during islanding. This method can detect islanding in as fast as 33.3 ms [58]. Najy et al.[59] have also proposed an accurate and efficient passive method that uses PCC voltage and frequency as islanding indicators. The proposed method was tested on various disturbances such as active and reactive power mismatches with constant RLC loads, dynamic loads during islanding, and fault disturbances under fully loaded and lightly loaded systems conditions. It can differentiate between islanding and non-islanding for closely matched load-DG rating, reducing the NDZ of the OV/UV and OF/UF methods.

(b) Combination of rate of voltage change (passive method) and real power shift (active method): if an average rate of voltage change (passive technique) cannot justify between islanding and other events in the system, a real power shift (active technique) will be activated to change the real DG power. According to the algorithm, voltage are measured and compared between V_{smin} and V_{smax} values. If the value lies between V_{smin} and V_{smax}, RPS is activated, which increases or decreases the real power generation on one of the DGs. The second stage of the algorithm compares values with V_{smaxU} (a set point to detect islanding). Islanding is detected when the values match the V_{smaxU}. The main advantages of this method are that it eliminates the need for disturbance injection (unlike any other active methods) and efficiently detects islanding. The proposed method has been validated in a distribution network in Aalborg, Denmark [60].

(c) Combination of voltage unbalance and current THD: both are the parameters for detecting islanding especially in the case of small changes in the load for DG. Three parameters are monitored for the final decision on islanding detection. At every sampling time, this method calculates the average voltage of 3-phase $VU_{avg,t}$, the $THD_{avg,t}$ average of the phase-A current, and the average voltage $V_{avg,t}$ of the line-to-line voltage. For large variations of DG load, the proposed method easily detects islanding through the $V_{avg,t}$ values, whereas for little variations, it checks the other monitoring parameters ($THD_{avg,t}$ and $VU_{avg,t}$). The proposed method has been validated on several distribution network conditions and is expected to be an effective islanding detection method for industrial fields [61].

(d) Combination of frequency, voltage magnitude, phase change, THD, various sequence voltage, current and power: Maldhar Padhee et al.[62] proposed the simulation of a novel islanding technique that uses features estimated by a novel FGNW algorithm. A certainty-factor-based FES is then constructed by using the most significant features obtained through the FGNW algorithm to differentiate between islanding and non-islanding (only the parameters that exhibit significant deviations are chosen as inputs for the FES). The simulation results show the proposed method able to detect islanding in less than one cycle.

The limits and the implementation procedure of the methods must be known before making any comparisons. All the methods discussed may have the following limits:

(a) Reduced power quality and system instability (owing to positive feedback)
(b) NDZ
(c) False operation or ineffectiveness (in multiple-DG configurations)
(d) High implementation costs.

Those limits cause active islanding detection to be more focused on. Still, despite the lower reliability of passive methods, they are sometimes combined with active methods to increase effectiveness (Table 4).

6. Conclusion

This paper comprehensively reviewed the research done on islanding detection. Anti-islanding techniques can be classified into two groups based on their location in the DG system: local or remote. In local, the detection algorithm is on the inverter side, whereas in remote, the detection is on the grid side. Local techniques, consisting of passive and active methods, have been discussed. Much research has been on active methods. This article also compared related anti-islanding standards with general NDZ for islanding. It also discussed every aspect of the principle methods in islanding detection. The comparison can help researchers determine the best method for their product.

Acknowledgment

This work was supported by the UMPEDAC (University of Malaya Power Energy Dedicated Advanced Centre), a HICoE (Higher Institution Centre of Excellence) of the Ministry of Higher Education Malaysia and Campus Network Smart Grid System for Energy Security (account number: H-16001-00-D000032).

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